

STANDARD FITS TEMPLATE FOR SIMULATED ASTROPHYSICAL SCENES WITH THE WFIRST CORONAGRAPH

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ABSTRACT

The science investigation teams (SITs) for the *WFIRST* coronagraphic instrument have begun studying the capabilities of the instrument to directly image reflected light off from exoplanets at contrasts down to contrasts of $\sim 10^{-9}$ with respect to the stellar flux. Detection of point sources at these high contrasts requires yield estimates and detailed modeling of the image of the planetary system as it propagates through the telescope optics. While the SITs might generate custom astrophysical scenes, the integrated model, propagated through the internal speckle field, is typically done at JPL. In this white paper, we present a standard file format to ensure a single distribution system between those who produce the raw astrophysical scenes, and JPL modelers who incorporate those scenes into their optical modeling. At its core, our custom file format uses FITS files, and incorporates standards on packaging astrophysical scenes. This includes spectral and astrometric information for planetary and stellar point sources, zodiacal light and extragalactic sources that may appear as contaminants. Adhering to such a uniform data distribution format is necessary, as it ensures seamless work flow between the SITs and modelers at JPL for the goals of understanding limits of the *WFIRST* coronagraphic instrument.

1. INTRODUCTION

The coronagraphic instrument (CGI) for the Wide-Field Infrared Survey Telescope (WFIRST) will be used to detect reflected starlight from exoplanets at planet-to-star contrasts of $\sim 10^{-9}$. The WFIRST-CGI will have multiple observing modes. These consist of discovery modes using a Hybrid Lyot Coronagraph (HLC; Trauger et al. 2016) coupled with broadband optical imaging for detection of exoplanets and debris disks, and a Shaped Pupil Coronagraph (SPC; Carlotti 2013; Riggs et al. 2014) and SPC disk mask (Zimmerman et al. 2016) coupled with an integral field spectrograph (IFS) for characterization.

To properly characterize the performance capabilities of the WFIRST-CGI and improve upon current post-processing data reduction techniques, simulated coronagraphic data of selected targets must be analyzed. Typically, an astrophysical scene is generated, whereby information of the target star, astrometric and flux information for planets and background point sources, and other astrophysical noise is accumulated and propagated through a speckle field to model the light from the astrophysical scene moving through the internal telescope optics. In most cases, these two tasks are done separately. Thus, to ensure seamless work flow, a standard distribution system of the raw and processed astrophysical scene is necessary.

In the following article, we outline an efficient method of creating and distributing the scene information by using a multi-extension Flexible Image Transport System (FITS) file. We begin in § 2 by describing each simulation component and the structure of the multi-extension FITS file. We then describe the format and required header keywords for the primary extension in § 3. Next, we describe the details for constructing the extensions that must hold table formatted information, such as fluxes and astrometric information of point sources, in § 4. Lastly we describe the details for constructing the extensions that hold the spectral data cubes of the exozodiacal emission and background galactic contaminants in § 5.

2. SUPPORTED DATA & FITS ADOPTION

A typical astrophysical scene will have multiple independent components, each described by a myriad of meta-data, simulated to the specifications of different observing modes, at varying complexities. Regardless of the instrumental

dependencies, each scene will be created using a combination of the following components:

- Astrometric information of generated point sources (background stars and planets).
- Contrast and flux information of the central star and point sources.
- Spectral data cubes of extragalactic background sources.
- Spectral data cubes of exozodiacal emission.

It is important to encode the individual elements of the astrophysical scene, thereby providing transparency and clarity. To encode each individual aspect of the astrophysical scene, we decided to package the data into a FITS file, each with their individual extension, encompassed as a single FITS file. In addition to the standard FITS header keywords (e.g., `BITPIX`, `NAXIS`, `EXTEND`, etc.), we outline the format for each section and allowed meta-data header information in the following sections.

2.1. General Format

Each simulation package will be a multi-extension FITS formatted file. A single FITS file will be unique to a single star and observation epoch, and include at the very least the primary extension described in § 3. Any additional extensions are optional and are not subject to being placed in any particular order. The extensions are however subject to standard names, and the user may access each by calling on the extension *name*. A list of acceptable extensions are listed in Table 2.1, with additional information in the succeeding sections.

Table 1. All Extension Labels and Descriptions.

Extension Name	Extension Type	Description
PRIMARY	PrimaryHDU	Primary header: Contains stellar and simulation parameters in header.
CONTRAST_BB	BinTableHDU	Broadband contrast and fluxes
CONTRAST_IFS	BinTableHDU	IFS contrast and fluxes
ASTROMETRY	BinTableHDU	Positional information of point sources
ZODI_BB	ImageHDU	Broadband exozodiacal image cube
ZODI_IFS	ImageHDU	IFS exozodiacal image cube
BACKGROUND_BB	ImageHDU	Broadband extragalactic image cube
BACKGROUND_IFS	ImageHDU	IFS extragalactic image cube

NOTE—General description of all possible extensions that may be included in the multi-extension FITS file. All extensions, except the **PRIMARY** extension, are optional.

3. STANDARD PRIMARY HEADER

The primary header of the FITS file is reserved to host information for the primary star. The primary header will not contain any image or table, but holds meta-data about the observed target in the headers. A required list of header keywords and associated data types are listed in Table 2.

Table 2. Primary Header FITS Keywords

Keyword	Data Type	Fixed Value	Description
SIMDATE	string (10-char)	...	Date of simulation YYYY-MM-DD
EPOCH	float	...	UT date of observation
OBJNAME	string	...	Target’s SIMBAD ID
RA_OBJ	float	...	Right Ascension (deg)
DEC_OBJ	float	...	Declination (deg)
PMRA	float	...	RA proper motion (mas/yr)
PMDEC	float	...	DEC proper motion (mas/yr)
PLX	float	...	Parallax (mas)
SPT	string	...	Spectral Type
V_OBJ	float	...	V band (mag)
B_OBJ	float	...	B band (mag)
J_OBJ	float	...	J band (mag)
H_OBJ	float	...	H band (mag)
KS_OBJ	float	...	Ks band (mag)
COMMENT	string	...	Comments related to simulation.

NOTE—Standard keywords in the PRIMARY extension. All these headers are required, and keywords cannot be changed.

4. TABLE DATA

4.1. Astrometry

Point need to have their astrometric information included in the **ASTROMETRY** extension. Instead of absolute coordinate information, coordinate offsets from the stellar center must be listed. The data must be encoded in a FITS binary table format. Columns are designated for each point source, and a maximum of two rows for each column are designated for offsets in right ascension and declination for the first and second row, respectively.

The designation for each point source (i.e., column title) is encoded in the **TTYPEi** keyword, where **i** is the i^{th} column. The column header for simulated planets can be listed as “Planet j Offset”, where j is the j^{th} simulated

planet. Background field stars can be listed as “Field Star k Offset”, where k is the k^{th} simulated field star. Neither j or k need to be equal to i . In addition, the column header can also be given custom titles, if the user wishes. For instance, planets can also be described by their official designation and/or additional model descriptions (e.g., “47UMa.c_model3.2”). The astrometric offsets should be in units of “arcseconds”, listed under the FITS keyword TUNIT*i*.

Table 3. Astrometry extension header keywords.

Keyword	Data Type	Fixed Value	Description
EXTNAME	string	ASTROMETRY	extension name
TFIELDS	int	...	number of table fields
FIELDCOL	int	...	Starting column of field star flux
PLCOL	int	...	Starting column of planet contrasts
TTYPE <i>i</i>	string	Planet j Offset or Field Star k Offset	Column Name.
TFORM <i>i</i>	string	E	Column Data Type
TUNIT <i>i</i>	string	arcsec	Column Units
COMMENT	string	...	Comments related to simulation.

NOTE—Standard keywords for the extension which contains the point-source astrometry.

4.2. Contrast & Fluxes

The flux of each point source in § 4.1 and the target star must be tabulated in the binary table CONTRAST_BB extension for broadband wavelengths and/or the CONTRAST_IFS extension, for IFS wavelengths. Columns are designated for each source, while each row corresponds to a different wavelength channel for the flux in each “cell”. In the case of simulated planets, the fluxes must be listed as a flux ratio, relative to the central star. The target star and any background field stars should have absolute fluxes in units of “Jy.” To simplify the modelling, the fluxes of the central star and background stars *must* be obtained using a flat response function over the listed bandpass be flat.

The number of rows is determined by the number of spectral channels the user wishes to encode. For broadband fluxes and contrasts, a maximum of four rows — one for each of the WFIRST-CGI broadband channels — can be added to the binary table. Broadband flux information must be included in the CONTRAST_BB extension only. The accompanying central wavelength and bandwidth must also be included into the header keywords CRWAVE*i* and BWWAVE*i*, respectively. Here, $i \in \{1, 2, 3, 4\}$, to denote the four WFIRST-CGI imager wavelength channels. Point sources simulated at the IFS channels will have fluxes calculated at a larger number of wavelengths and included in the CONTRAST_IFS extension only. For the latter, instead of listing each wavelength in the header, we require that the wavelength range and resolution be listed, from which the wavelength for each row can be calculated.

For both extensions, the first column will always include the target spectrum, indicated by the header keyword STARCOL=1. The number of simulated field stars/planets must also be indicated in the header, as well as the starting column for each type of point source. The combination of the number of sources, starting column, and column title will allow the user to determine where each point source spectrum is encoded. As described in § 4.1, point source columns can be designated using a generic sequential name under the TTYPE keyword, as shown in Tables 4 and 5, or with a custom title. The full list of IPAC header keywords for the broadband and IFS flux extensions can be found in Tables 4 and 5.

Table 4. Broadband contrast extension header keywords.

Keyword	Data Type	Fixed Value	Description
EXTNAME	string	CONTRAST_BB	extension name
CRWAVE <i>i</i>	int	...	Broadband channel <i>i</i> center wavelength (nm)
BWAVE <i>i</i>	int	...	Broadband channel <i>i</i> bandwidth (%)
STARCOL	int	1	Begin Stellar Flux Column
FIELDCOL	string	...	Begin Field Star Flux Column
PLCOL	string	...	Begin Planet Contrast Column
NPL	string	...	Number of Planets
NFIELD	string	...	Number of Field Stars
TTYPE <i>i</i>	string	Stellar Flux/Field Star <i>i</i> Flux/Planet <i>i</i> Contrast	Column Name
TFORM <i>i</i>	string	E	Column Data Type
TUNIT <i>i</i>	string	Jy or CONTRAST	Column Units
COMMENT	string	...	

NOTE—Standard keywords for the extension which contains contrast and flux at broadband detector channels. The stellar flux must be the first column in the table. The column name depends on whether it is flux for the central star, background stars or contrast for simulated planets.

Table 5. IFS contrast extension header keywords.

Keyword	Data Type	Fixed Value	Description
EXTNAME	string	CONTRAST_IFS	extension name
MINWAVE	int	...	Blue end of IFS (nm)
MAXWAVE	int	...	Red end of IFS (nm)
NWAVE	int	...	Number of IFS slices
STARCOL	int	1	Begin Stellar Flux Column
FIELDCOL	string	...	Begin Field Star Flux Column
PLCOL	string	...	Begin Planet Contrast Column
NPL	string	...	Number of Planets
NFIELD	string	...	Number of Field Stars
TTYPE <i>i</i>	string	Stellar Flux or Field Star <i>i</i> Flux or Planet <i>i</i> Contrast	Column Name

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Table 5 (*continued*)

Keyword	Data Type	Fixed Value	Description
TFORMi	string	E	Column Data Type
TUNITi	string	Jy or CONTRAST	Column Units
COMMENT	string	...	...

NOTE—Standard keywords for the extension which contains contrast and flux at IFS detector channels. The stellar flux must be the first column in the table. The column name depends on whether it is flux for the central star, background stars or contrast for simulated planets.

5. SPECTRAL IMAGE CUBES

Spectral data cubes will be used to encode exozodiacal and background galactic emission. These images should not include instrumental effects. In other words, the flux from the background galaxies and exozodiacal light should be encoded in the spectral cube as raw astrophysical emission, prior to their light entering the telescope. If the user wishes to include WCS data, they may do so by including the WCS header keywords in each extension (WCSAXES, CRPIX1, CRPIX2, CDELTA1, CDELTA2, CTYP1, CTYP2, CRVAL1, CRVAL2, LATPOLE). However, these are not mandatory.

5.1. Exozodiacal Images

Simulated exozodiacal images are to be included in the ZODI_BB and ZODI_IFS extensions, depending on whether the images were generated at broadband wavelengths or at finer IFS channels. The images should be packaged as image cubes of size $m \times m \times N$, where m is the number of pixels in a single slice and N is size of the spectral dimension.

Similar to the guidelines in § 4.2, images at broadband wavelengths must be specified using the CRWAVEi and BWAVEi header keywords, while IFS generated images should include the wavelength range and resolution, as described in Tables 6 and 7. The pixel intensity must be in absolute flux units of “Jy”. This must also be reflected in the standard header keyword BUNIT = “Jy”.

Table 6. Broadband exozodiacal image-cube extension header keywords.

Keyword	Data Type	Fixed Value	Description
EXTNAME	string	ZODI_BB	extension name
OBSMODE	string	BB	Broadband setting
CRWAVEi	int	...	Broadband channel i center wavelength (nm)
BWAVEi	int	...	Broadband channel i bandwidth (%)
BUNIT	string	Jy	Flux Units
COMMENT	string	...	...

NOTE—Standard keywords for the extension which contains the simulated exozodiacal image cube at broadband detector channels.

Table 7. IFS exozodiacal image-cube extension header keywords.

Keyword	Data Type	Fixed Value	Description
EXTNAME	string	ZODLIFS	extension name
OBSMODE	string	IFS	IFS setting
MINWAVE	int	...	Blue end of IFS (nm)
MAXWAVE	int	...	Red end of IFS (nm)
NWAVE	int	...	Number of IFS slices
BUNIT	string	Jy	Flux Units
COMMENT	string	...	...

NOTE—Standard keywords for the extension which contains the simulated exozodiacal image cube at the IFS detector channels.

5.2. Extragalactic Background Images

Data cubes containing simulated extragalactic background images should be packaged in the `BACKGROUND_BB` and `BACKGROUND_IFS` extensions, in a similar format to the exozodiacal data cubes in § 5.1. Similarly, the data cubes will have dimensions of $m \times m \times N$.

Table 8. Broadband Background extragalactic image-cube extension header keywords.

Keyword	Data Type	Fixed Value	Description
EXTNAME	string	BACKGROUND_BB	extension name
OBSMODE	string	BB	Broadband setting
CRWAVE i	int	...	Broadband channel i center wavelength (nm)
BWAVE i	int	...	Broadband channel i bandwidth (%)
BUNIT	string	Jy	Flux Units
COMMENT	string	...	...

NOTE—Standard keywords for the extension which contains the simulated extragalactic background image cube at the broadband detector channels.

Table 9. IFS Background extragalactic image cube extension header keywords.

Keyword	Data Type	Fixed Value	Description
EXTNAME	string	BACKGROUND_IFS	extension name
OBSMODE	string	IFS	IFS setting
MINWAVE	int	...	Blue end of IFS (nm)
MAXWAVE	int	...	Red end of IFS (nm)
NWAVE	int	...	Number of IFS slices
BUNIT	string	Jy	Begin Field Star Flux Column
COMMENT	string	...	...

NOTE—Standard keywords for the extension which contains the simulated extragalactic image cube at the IFS detector channels.

6. CONCLUSION

Our goal is to provide a standard file system for packaging of raw astrophysical scenes, simulated for the WFIRST-CGI. Since the modelers will need to incorporate different components in the scene, we present a multi-extension FITS format to allow for efficient data sharing between modelers and SIT teams.

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